ARCHAEOLOGY

Above and below the Maya forest

Advanced remote sensing technology raises questions about settlement and land use

By **Anabel Ford**[1] *and* **Sherman Horn**[2]

Reports of lost cities in the Maya forest began with the remarkable pictorial folios that Stephens and Catherwood produced from their journeys in the 1830s (*1*) and that inspired the Carnegie Institution of Washington's expeditions in the early 20th century (*2*). This research focused on major architecture: the grandest temples, plazas, tombs, and palaces built for Maya aristocrats. The singular attention paid to rulers illuminated Maya politics and religion but left a major lacuna in knowledge of the populace. To fill this gap, later fieldwork mapped the humble housemounds to interpret settlement patterns at the detailed site scale (*3*–*5*). On page 1355 of this issue, Canuto *et al*. (*6*) use a remote sensing method called light detection and ranging (lidar) to examine regional-scale settlement patterns and implications for sustainability in the Maya forest. Their conclusions support extensive settlement densities, as has been expected, and suggest substantial land modifications that affect assessments of sustainability.

Twentieth-century scientific surveys in the Maya area (*4*–*6*) typically proceeded by cutting a breach—a *brecha*—through the jungle and then using paced distances and compass bearings to compile a mapped 250- to 500-m-wide transect. Striking into the unknown, surveyors relied on calculated azimuths, basic ordnance maps, and aerial photos. These tools served archaeologists well, providing a basis for discovering settlement patterns and interpreting land use, as seen at El Pilar where settlement patterns have demonstrated sustainability at the local scale (*7*, *8*). Does lidar supersede the traditional tools of the tropical surveyor's kit? The revelation of the topography below the forest canopy by lidar, which illuminates target areas with laser light and measures reflectance to create three-dimensional representations of the ground surface, is like a magic wand. Rather than striking into the unknown, we now can see the landscape and features that may relate to ancient settlement. The interpretations of cultural remains are only impressions, however, until the remotely sensed images are verified by teams on the ground. Interpretations of ancient land use depend on archaeological survey to locate and document prehistoric settlements. Understanding settlement patterns over large areas requires extrapolation from samples of surveyed land, which has proved challenging in the densely forested lowlands occupied by the ancient Maya. Lidar clearly visualizes the geographic essentials critical to understanding settlement patterns: topography, drainage, and slope. Canuto *et al*. now bring together 18 archaeologists working in 10 areas, covering more than 2000 km², to examine regional relationships between environment and settlement. In addressing land use sustainability in the Maya Lowlands, where contemporary land use is expanding at the expense of the forest, Canuto *et al*. suggest that the ancient Maya could have faced similar issues. We, too, have been working with lidar at El Pilar to address sustainability in the tropics (*9*) and to ask whether deforestation is the only outcome of ancient Maya settlement expansion, as the prevailing narrative in Maya archaeology proclaims (*10*).

Dense forest covers the Verdant Maya Biosphere Reserve, as seen from El Pilar.

On the basis of a concordance of lidar visualizations, existing maps, and preliminary field examinations, Canuto *et al*. estimate population densities of 80 to 120 persons/km², which are extrapolated to a population of 7 to 11 million across the 95,000 km² of the central Maya Lowlands in the Late Classic (600–900 CE). These broad extrapolations are based on the 61,480 structures identified in the lidar visualizations. Canuto *et al*. used existing maps to interpret unvisited areas. This procedure will produce reasonable results at the 1:250,000 regional scale offered by Canuto *et al*., and even at the 1:50,000 local scale (*8*). However, fieldwork is needed at the detailed 1:10,000 site scale. Large features are clearly visible. Field validation should follow up on the proposed terrain modifications (such as the wetland drainages) as well as small, low features (such as isolated structures) that affect our understanding of human-environment interactions (*11*).

Interpretations by Canuto *et al*. raise intriguing hypotheses. The authors define a rural-to-urban continuum based on preliminary structure density and propose a threshold of sustainability beyond which food importation would be required. They identify features in lidar imagery, such as terraces and canals, that are ascribed to agricultural intensification. Investing in infrastructure to overcome environmental limitations along with putting marginal land (areas with too much or too little water) under cultivation is one strategy for intensifying food production. But what about strategies that intensify food production without infrastructure? Agricultural intensification strategies that rely on labor, skill, and scheduling can increase food yields but are not reflected in surface features detected by lidar. Intensified food production can result from the management of infield forest gardens around structures as well as in outfields. Again, on-site geographic and archaeological validation will resolve imagery ambiguities and provide the appropriate scale to assess land use alternatives and to validate agro-engineering features.

The terrestrial features revealed by lidar technology are indeed exciting and have opened the door to the next step of studying the Maya forest: assessment of the imagery. As exciting as the imagery is, we need to understand the nuances of where small, and

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presumably domestic, structures may or may not be present. With standard Global Positioning Systems, one can locate and validate features identified remotely in lidar imagery within 7- to 14-m accuracy. Structure locations and densities as well as the "zones of intensive cultivation" may well change with field inspection, as lidar has a tendency to image false positives (*11*). The archaeological survey methods developed in the Maya forest over the past 60 years are basic to the validation process (*3*–*5*). Archaeologists with "boots on the ground" will be able to determine whether proposed structures are instead treefalls, palm debris, or technical errors in the lidar visualizations. Equally challenging are linear features—presumed signatures of land modifications (particularly in wetlands)—that may be artifacts of lidar visualizations. While lidar technology has improved over the past decade, it is the innovative visualization methods that are critical (*12*). Assessment of lidar imagery will help the field evolve the use of this technology. These developments are where the greatest prospects for the future of archaeology lie.

Canuto *et al*. recognize that fieldwork is the way forward and prophetically conclude that lidar will become indispensable for settlement research. The authors also present an excellent example of a regional scale evaluation of settlement patterns, and by proxy, to analyze sustainability. They suggest that the patterns they elucidated are not to be solely based on geography; political and economic forces must be evoked to explain Maya land use. Their interpretation provides critical hypotheses for future testing and is a call to action for archaeologists to scrutinize the findings with survey at the detailed site scale. As usual, the devil is in the details. ■

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CANCER

How dormant cancer persists and reawakens

Insights reveal possible avenues to prevent metastasis

By **Julio A. Aguirre-Ghiso**

Treatment of stage IV cancer, when metastases are detectable by conventional imaging methods, is commonly the only strategy we have to defend against this lethal stage of disease. However, the seeds of those lesions, the disseminated cancer cells (DCCs), can reside in a patient's organs for long periods before their outgrowth (*1*). DCCs are proposed to be able to persist for years because they interpret homeostatic signals from the host microenvironment and respond by entering a long-lasting dormant state, with occasional cell divisions (*1*, *2*). In response to signals not yet fully identified, dormant DCCs reawaken and grow into larger lesions. So why not intervene earlier when DCCs are dormant? This has presented a challenge because the biology of DCC dormancy was mechanistically unclear and there was no way to determine whether DCCs were dormant. However, two decades of mechanistic research (*1*, *2*) and recent work by Pommier *et al*. (*3*) and on page 1353 of this issue by Albrengues *et al*. (*4*) have provided important insights into the microenvironmental control of DCC dormancy and reawakening that leads to metastasis, which could have therapeutic implications.

"...disseminated cancer cells... can reside in... organs for long periods..."

The dormancy of DCCs has been mostly explained by the ability of these cancer cells to enter quiescence, a reversible and programmed growth arrest (*1*). Clinical evidence and experimental models support this mechanistic view, which helps to explain why in some cancers (for example, estrogen receptor–positive breast cancer and prostate cancer), patients can be free of disease for more than a dozen years. The implications of this biology are profound; it offers a window of opportunity to treat metastasis early and to understand how host and epigenetic factors override the driver genetics that supposedly can only fuel cancer growth. This new theory of metastasis progression (*1*) has led to innovative questions such as those addressed by Albrengues *et al*. and Pommier *et al*.

Pommier *et al*. investigated how DCCs evade the immune system. They found that mice immunized against pancreatic cancer cells produced an immune response that killed most of the DCCs when they were subsequently engrafted. But some solitary DCCs persisted, which suggests that $CD8^+$ T cells did not recognize them. Careful analysis confirmed that DCCs are quiescent and lack expression of the epithelial cell marker E-cadherin (epithelial cadherin), but do not undergo an obvious epithelial-mesenchymal transition, which has been linked to increased cancer cell adaptability to changing microenvironments and initiation of metastasis. Importantly, they found that dormant DCCs activate components of the unfolded protein response (UPR), a proteotoxicity survival pathway (*5*). The UPR was previously found to promote the survival of dormant cancer cells implanted in immunodeficient mice [patient-derived xenograft (PDX)], and it has been linked to how cancer cells respond both to internal (metabolic) stress and external stress (adaptation to foreign extracellular matrix composition) (*6*, *7*). Pommier *et al*. found that the UPR caused posttranscriptional downregulation of major histocompatibility complex (MHC) class I molecules, which present antigens to $CD8^+$ T cells. Thus, the UPR also controls how dormant DCCs are interacting with the immune microenvironment. This decrease in MHC class I expression was associated with activated UPR and rendered dormant DCCs undetectable by $CD8^+$ T cells; restoration of UPR activity caused DCCs to reexpress E-cadherin and MHC class I, reversing the immune-evasive phenotype so that $CD8^+$ T cells could detect them in vivo.

Different cancer types exhibit predictable metastatic distribution, but the timing of relapse is variable and appears to be random. This has prompted the suggestion that both DCC-intrinsic and microenvironmental factors influence the rate of relapse (*1*, *2*). Albrengues *et al*. investigated what reactivates dormant DCCs. A prevalent theory is

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